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14. ABSTRACT
Understanding and controlling jet noise has been the focus of analytical, computational and experimental research for decades, however methods of measurably controlling-reducing jet noise in an efficient and robust manner remain evasive. Previous research has shown that coherent structures are one of the dominant sources of jet noise for both supersonic as well as subsonic jets. These structures are generally regarded as manifestations of the initial shear layer instabilities that originate at the nozzle exit.

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Report Title

High Temperature Supersonic Jet Noise - Fundamental Studies and Control using Advanced Actuation Methods

ABSTRACT

Understanding and controlling jet noise has been the focus of analytical, computational and experimental research for decades, however methods of measurably controlling-reducing jet noise in an efficient and robust manner remain evasive. Previous research has shown that coherent structures are one of the dominant sources of jet noise for both supersonic as well as subsonic jets. These structures are generally regarded as manifestations of the initial shear layer instabilities that originate at the nozzle exit.

Under this effort, we addressed this problem with a multi-pronged approach to better understanding and controlling Jet Noise at realistic conditions. We developed a framework using optimal perturbation theory which predicts the most unstable modes that are expected to grow inside the nozzle. Such amplified perturbations are expected to be the source of large scale turbulent structures that develop in the jet shear layer contributing to noise from this source. Along a related but distinct path, we developed very high frequency actuators to directly introduce disturbances in the jet shear layer at frequencies that have been shown to suppress turbulence (Zaman & Hussain3) and hence may lead to jet noise suppression.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/15/2016	1.00	. Characterization and Validation of an Anechoic Facility for High-Temperature Jet Noise Studies, 46th AIAA Fluid Dynamics Conference. 03-JUN-16, Washington, DC. : ,
08/15/2016	2.00	. Active Control of Mach 0.9 Jet Using High Frequency Excitation, 53rd AIAA Aerospace Sciences Meeting. 05-JAN-15, Kissimmee, Florida. : ,
08/15/2016	3.00	. Supersonic Jet Impingement on a Model-scale Jet Blast Deflector, 54th AIAA Aerospace Sciences Meeting. 04-JAN-16, San Diego, California, USA. : ,
08/15/2016	4.00	. Development and Characterization of Ultra-High Frequency Resonance-Enhanced Microjet Actuator, 43rd AIAA Fluid Dynamics Conference. 24-JUN-13, San Diego, CA. : ,
08/15/2016	5.00	. Flow and Acoustic Features of a Mach 0.9 Jet Using High Frequency Excitation, AIAA Sci Tech 2015. 04-JAN-16, San Diego, CA. : ,
08/15/2016	6.00	. Recent Developments in High Bandwidth Pulsed Micro-Actuators for Fluid Applications, 9th International Conference on Nano/Molecular Medicine and Engineering. 15-NOV-15, Hawaii. : ,

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Received Paper

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(d) Manuscripts

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Manuscripts:

Books

<u>Received</u> <u>Book</u>

TOTAL:

<u>Received</u> <u>Book Chapter</u>

TOTAL:

Patents Submitted

Patents Awarded

Awards

F. Alvi, Cummins Professor of Engineering, 2014

P. Upadhyay, Amelia Earhart Fellow (awarded by Zonta International), 2014-15

T. Worden, SMART Fellowship, 2015 - Present

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Joseph Craft	0.33	
Brandon Davis	0.33	
Puja Upadhyay	0.75	
FTE Equivalent:	**1.41**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Ali Uzun	0.75
FTE Equivalent:	**0.75**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Alvi, Farrukh	0.07	
Chiang Shih	0.04	
FTE Equivalent:	**0.11**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Alex Baldwin	0.20	Mechanical Engineering
Joseph Craft	0.15	Mechanical Engineering
Malcolm Harmon	0.20	Mechanical Engineering
Roslyn Shanklin	0.25	Industrial Engineering
Devon Stubbs	0.20	Mechanical Engineering
Ryan D'Ambrosia	0.50	Mechanical Engineering
FTE Equivalent:	**1.50**	
Total Number:	**6**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	3.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	3.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	2.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	2.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	2.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

1 a. Florida State University		1 b. Sponsored Research Administration		
		874 Traditions Way, Third Floor		
		Tallahassee	FL	323064166

Sub Contractor Numbers (c): 032078, 035111
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Collaborative effort on the design, integration, and implementation of novel actuators for
Sub Contract Award Date (f-1): 5/1/13 12:00AM
Sub Contract Est Completion Date(f-2): 4/30/16 12:00AM

1 a. Florida State University		1 b. 97 South Woodward Avenue, Third		
		Tallahassee	FL	323060001

Sub Contractor Numbers (c): 032078, 035111
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Inventions (DD882)

Scientific Progress

PLEASE SEE ATTACHED FINAL REPORT. The technical report details the scientific progress and accomplishments.

Technology Transfer

Interactions with the following individuals promoted the transfer of technologies developed in this research:

DOD Scientists: Dr. J. Spyropoulos, NAVAIR (on Jet Noise)

Industry:
Christopher Harris (NORTHRUP GRUMMAN Corp on Jet Noise and Active Flow Control)
Edward Whalen (BOEING,on Jet Noise and Active Flow Control)

<u>Final Report – August 2016</u>

High Temperature Supersonic Jet Noise – Fundamental Studies and Control using Advanced Actuation Methods

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Statement of the Problem Studied

Understanding, predicting and eventually controlling jet noise is a problem that has been the focus of analytical, computational and experimental research for a number of decades. As a result, our understanding of this phenomenon has improved significantly. However, methods of measurably controlling-reducing jet noise in an efficient and robust manner remain evasive. Stricter regulations on aircraft noise levels as well as noise certification requirements for airplanes have made the issue of jet noise even more pressing. Among the principal outcomes of previous decades of research is the recognition that coherent structures are one of dominant sources of jet noise for both supersonic as well as subsonic jets. These structures, interchangeably referred to instability waves, coherent structures, or wave packets, are generally regarded as the manifestations of the initial shear layer instabilities that originate at the nozzle exit. Crow and Champagne[1] and Moore[2] were among the first to observe and clearly exhibit the presence of these structures in axisymmetric turbulent jets. This recognition has led to numerous attempts at controlling noise through manipulation of these large-scale structures – the results have been mixed in part due to an incomplete understanding of the source of these structure and availability of actuators with the requisite dynamic range and control authority.

Under a three-year effort, we pursued an aggressive research program that addresses this problem in a multi-pronged approach to *better understanding and controlling Jet Noise at realistic conditions*. Along an analytical-theoretical path, we develop a framework using *optimal perturbation theory* which predict the most unstable modes that are expected to grow inside the nozzle. Such most amplified perturbations are expected to be the source of large scale turbulent structures that develop in the jet shear layer contributing to noise from this source. Along a related but distinct path, we develop and implement very *high frequency actuators* to directly introduce disturbances in the jet shear layer at frequencies that have been shown *to suppress turbulence* (Zaman & Hussain[3]) and hence may lead to *jet noise suppression*.

Summary of the Most Significant Results

Background

Over the past few decades, the role of coherent structures as the dominant source of noise has been widely investigated for both supersonic as well as subsonic jets. These structures (or instability waves/wave packets) , first clearly observed by Crow and Champagne[1] and Moore[2] in axisymmetric jets, are generally regarded as the manifestations of shear layer instabilities that are thought to be initiated at/near the nozzle exit. Motivated by these findings, a large body of research has experimentally and/or computationally supported the role of the large scale structures in the far-field noise radiation in supersonic as well as subsonic jets [4-10]. These structures are spatially coherent, non- compact noise sources that are primarily responsible for low frequency noise radiation, and mainly dominate the aft angle directivity.[7] Therefore, the primary focus of jet noise control research has aimed at disrupting the growth and evolution of the large scale structures to reduce the radiated noise.

In the past few decades, development of many passive as well as active flow control strategies for noise reduction have been given serious consideration. Passive methods have been used in the form of chevrons, nozzle inserts[10-16], among others where the emergence of streamwise vorticity is known to be one of the main mechanism of control. These passive techniques dramatically enhance mixing/entrainment, thereby shortening the jet plume length and reducing the aft-angle noise in the far-field. However, the increased mixing and enhanced turbulent fluctuations often lead to a significant high frequency penalty. Moreover, these passive modifications to the nozzle are permanent, and hence the thrust penalty associated with them during off-design conditions is a major disadvantage. To minimize this loss in performance and allow selective use of control, many active flow control devices have been investigated. Steady control has been popular in the form of microjet injection[12, 17–19], fluidic chevrons and inserts[20-22]. In the recent years, steady microjet injection has shown great promise where the mixing characteristics of the jet are significantly altered due to the induced streamwise vorticity resulting in turbulence suppression and reduction in far-field noise.[12]

Unsteady excitation, which is one of the main thrusts of this study, is another active flow control technique that has gained significant popularity in the past few decades, where unsteady control methods can be roughly divided into low frequency actuation/control and high frequency control. Zaman and Hussain[3] showed that excitation frequencies corresponding to the initial shear layer instabilities $St_\theta \approx 0.012 - 0.017$ resulted in a substantial suppression of turbulence in the jet near field, where, $St_\theta = f\,\theta/U_j$ is the Strouhal number based on the initial momentum thickness (θ). They suggested that the maximum amplification of disturbances occurs for excitation at $St_\theta \approx 0.017$, which causes rapid growth, saturation, and decay of the instability waves, preventing the formation of energetic vortices. Hussain and Hasan[23] suggested that the far-field noise reduction was a direct consequence of near-field turbulence suppression, and demonstrated broadband reduction of far-field noise for $0.01 < St_\theta < 0.02$. The use of plasma actuators[24-25] has also demonstrated some effect of unsteady forcing on noise. However, the effect of unsteady forcing has been inconsistent and inconclusive, often encumbered by either limited frequency range of actuation and/or limited control authority.

Current Study

In this research program, we tackle the jet noise problem through control of large scale structures using two distinct but related approaches. In the first approach, we use *high frequency actuation* with the aim of inhibiting the formation of large scale coherent structures to attenuate noise. This is accomplished by designing and implementing Resonance-Enhanced Microjet (REM) actuators, a class of unsteady actuators capable of providing strong momentum perturbations over a large range of frequency, up to 60+ kHz. In the second approach, we explore an *upstream perturbation seeding*, method where ‘seed perturbations’ may be introduced in the inlet flow upstream of the nozzle at selected frequencies/wavelengths that are expected to be selectively amplified in the nozzle boundary layer. As a result we anticipate controlling not only the initial shear layer thickness (hence its stability characteristics), but also the energy-frequency spectrum within. It is anticipated that this will have a notable impact on the shear layer dynamics, especially in terms of the evolution of the large-scale structures and the resulting noise field, imparting spatio-temporal features to the otherwise broadband noise field. This can potentially make the shear layer more amenable to active control by providing wavelength-frequency that can be targeted for control. The backbone of this approach is the development and implementation of *optimal perturbation theory* which is expected predict the most unstable modes that should grow preferentially inside the nozzle; thus guiding the location and characteristics of actuators that can be used to provide the seed perturbations. A summary of the significant outcomes along these two research paths is described in subsequent sections.

Control of High Speed Jets using High Frequency Excitation

Here we explore the use of High Frequency (HF) excitation for active control of high speed jets for noise reduction. It is well known that large scale coherent structures in the jet shear layer are the most dominant source of turbulent mixing noise. These structures primarily radiate low frequency noise and are highly directional, mainly governing radiation in downstream or aft angles. Therefore, one of the main goals of high frequency control is to inhibit the formation of large scale coherent structures to attenuate the radiated noise.

Actuator Development and Characterization

To this end, we designed and characterized two high-frequency (20 kHz and 50 kHz, nominally) Resonance-Enhanced Microjet (REM) actuators. Extensive benchtop characterization using acoustic measurements and high magnification Schlieren were carried out to test the actuators' performance at various set of input parameters. Acoustic measurements along with flow visualization demonstrated that these actuators are capable of producing high-amplitude, supersonic/transonic microjets at discrete frequencies, where these REM actuators produced where high perturbations up to 70 kHZ. An example of the supersonic flowfield produced by this actuator can be seen in the high-magnification, phase-conditioned micro Schlieren images in Fig. 1. The aeroacoustic properties of the same actuator is seen in the spectrogram shown in Fig. 2. The details of these results were presented at the **43rd Fluid Dynamics conference in San Diego, CA (2013)**, which is included in the Appendix.

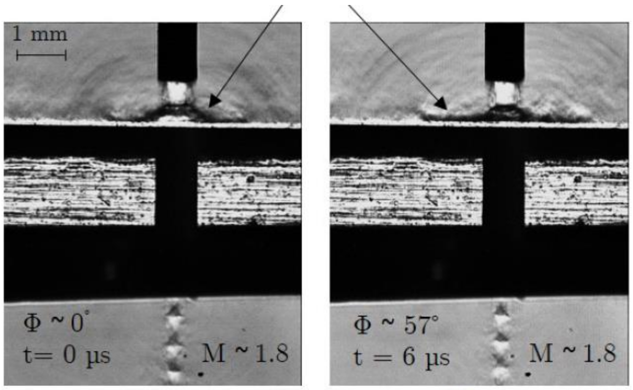


Fig. 1: Schlieren images for the nominally 20kHz actuator showing the evolution of flow at two phases.

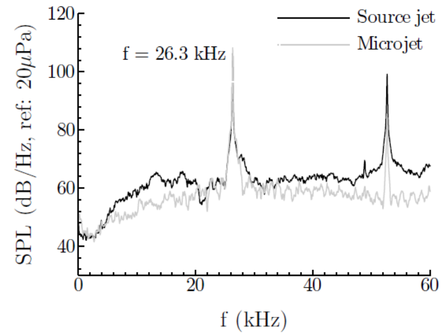
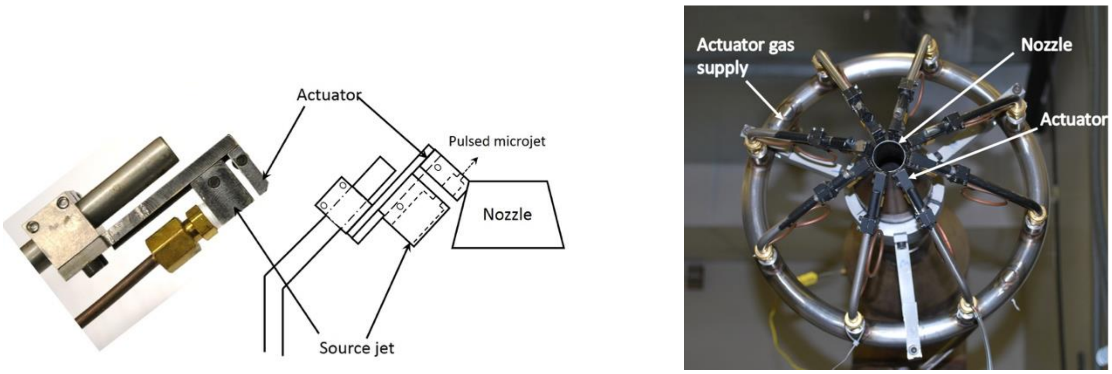


Fig. 2 - Aeroacoustic properties of the 20kHz (nominal) actuator.

Implementation of High Frequency Excitation for Jet Noise Control

Following benchtop characterization studies, a preliminary implementation of these actuators was performed on a Mach 0.9 ($Re_D = 5 \times 10^5$) free jet flow field. The primary goal of control was to reduce radiated noise by suppressing growth of the acoustically dominant large scale structures in the shear layer. A convergent axisymmetric nozzle with an exit diameter (D) of 1 in. was used to produce a Mach 0.9 jet with a Nozzle Pressure Ratio (NPR) = 1.69 and Temperature Ratio (TR) ≈ 1. Eight actuators with nominal frequency of 20 kHz were azimuthally distributed at the nozzle exit. The actuators were oriented such that the resulting pulsed microjets (d = 400 μm) penetrated the shear layer at an angle of 60^o from the vertical. Preliminary acoustic measurements were performed using a near-field microphone array placed 15D from the jet centerline, where D is the jet exit diameter. This linear array consisted of 7 microphones placed every 10° between 90° and 150° measured in the pilot forward configuration. In addition to near field acoustics, limited flow field measurements using particle image velocimetry (PIV) were performed to investigate the influence of high-frequency excitation on the evolution of the jet. Planar PIV was performed in the jet central plane in the streamwise direction and limited stereoscopic PIV was performed in select cross sectional planes of the jet.

Acoustic measurements revealed that high-frequency forcing reduces radiated noise at low to moderate frequencies for all observation angles. Moreover, noise reduction observed for all polar angles were fairly uniform, where OASPL reductions of 1.8 dB and 1.6 dB were observed for microphones at 90° and 150° degrees, respectively. In addition to suppression at low to moderate frequencies, an increase in noise levels at high frequencies (St_D > 1.8), resulting from resonant noise of the actuators, was observed in the near field. Preliminary flow field measurements revealed that high-frequency control significantly thickens the initial shear layer. Moreover, results also indicated that overall turbulent fluctuations are reduced due to microjet injection. The results for these preliminary experiments were presented at the ***53rd AIAA Aerospace Sciences Meeting Kissimmee, Florida, 2015 (AIAA 2015-0299).*** Details on actuator design, characterization, and implementation along with near field acoustic results are also published in ***Experiments in Fluids, 2016, 57:88, DOI*** *10.1007/s00348-016-2164-2.*



(a) (b)

Fig. 3: Implementation of high-frequency REM actuator at the nozzle exit showing (a) actuator orientation at the nozzle exit (b) final actuator assembly with the actuators, nozzle, and the supply ring

As discussed above, preliminary flow and acoustic measurements of the jet flow field with control showed promise in terms of turbulence suppression and attenuation of radiated noise in the near field. However, these initial set of flow measurements lacked the spatial resolution to adequately reveal all the pertinent features of the developing shear layer. Moreover, near field acoustic measurements were performed in a non-anechoic environment. To this end, the current study focuses on acquiring quality flow and noise measurements to better examine the influence of high-frequency control on the mean and turbulent properties of the jet as well as radiated noise in the far field. The effect of control on the developing shear layer is explored in great detail using planar as well as stereoscopic PIV at higher resolution. Planar PIV was performed in the central plane of the jet in the streamwise direction, spanning a distance of 6.5D. In addition to this, limited zoomed in view of the initial shear layer was obtained by performing planar PIV in the jet central plane, spanning an axial distance of approximately 4D. Stereo PIV was performed at every 0.5D for jet cross planes between 1.5D and 5D and two additional cross planes at 6D and 7D. Moreover, far-field acoustic measurements were performed in the anechoic high-temperature jet facility using a circular arc array of microphones placed at a distance of 100D measured from the center of the nozzle exit. The array consisted of eight microphones placed every 10° between 90° and 150° measured from the jet inlet axis. The main goal of this study is to explore the mechanisms associated with high-frequency control, mainly focusing on the changes in noise levels and observed modifications in the flow features. Representative results from the analysis of the acquired flow and noise data are discussed below.

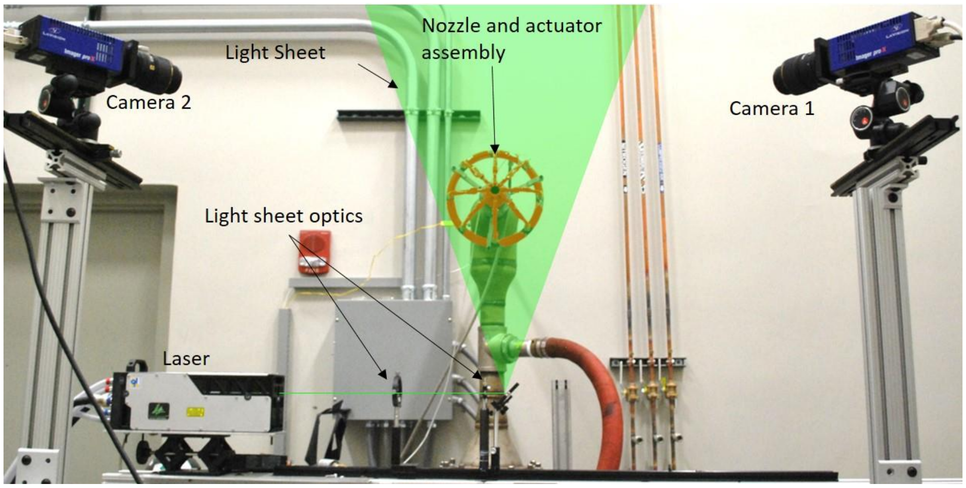


Fig. 4: Experimental setup for stereoscopic PIV showing the light sheet, cameras, optics and the nozzle assembly.

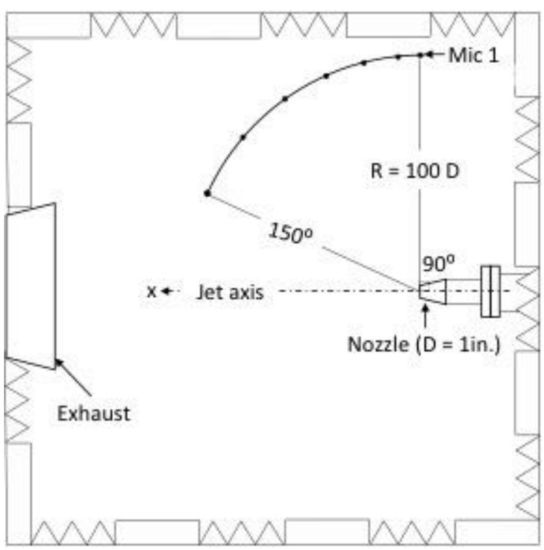
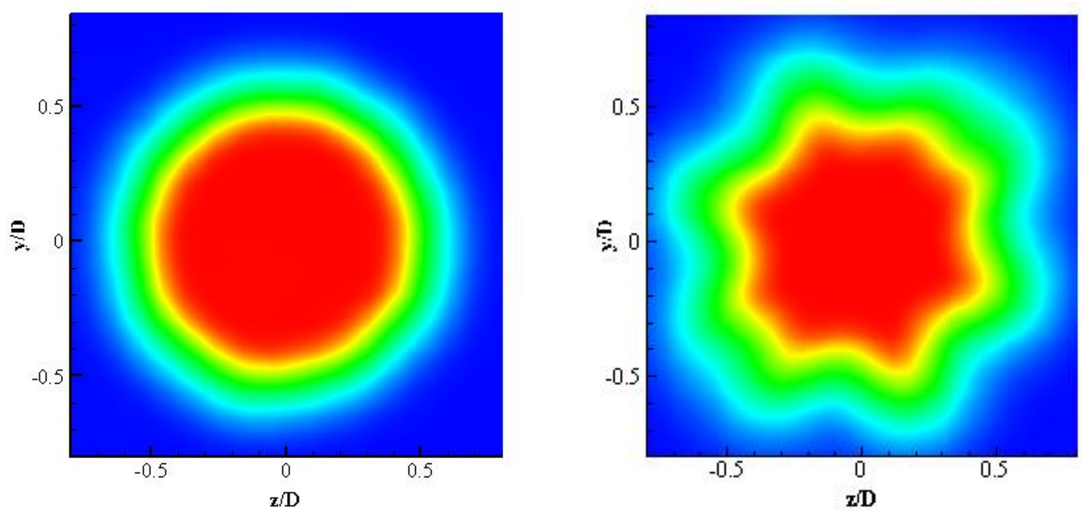


Fig. 5: Experimental setup for acoustic measurements showing the nozzle, microphone arc, and microphones in the anechoic chamber

Cross stream PIV measurements for control cases revealed that the interaction of forced microjets with jet shear layer results in the formation of strong streamwise vortex pairs. These counter-rotating vortex pairs were observed to significantly modify the initial velocity profile of the jet, resulting in a prominently undulated or corrugated shear layer. Downstream cross plane measurements indicated that these vortex pairs grow as they convect downstream, increasing the local entrainment and significantly thickening the initial shear layer. Preliminary investigation of turbulent quantities showed that high-frequency forcing results in an increase in fluctuation levels for near injection regions. However, for the downstream axial locations, control results in a global reduction of turbulent quantities. Both peak radial turbulence intensity as well as peak turbulent kinetic energy showed a maximum reduction of about 15% as a result of control. Moreover, cross plane PIV results clearly demonstrated that the observed modification is achieved across the entire jet cross section.



(a) (b)

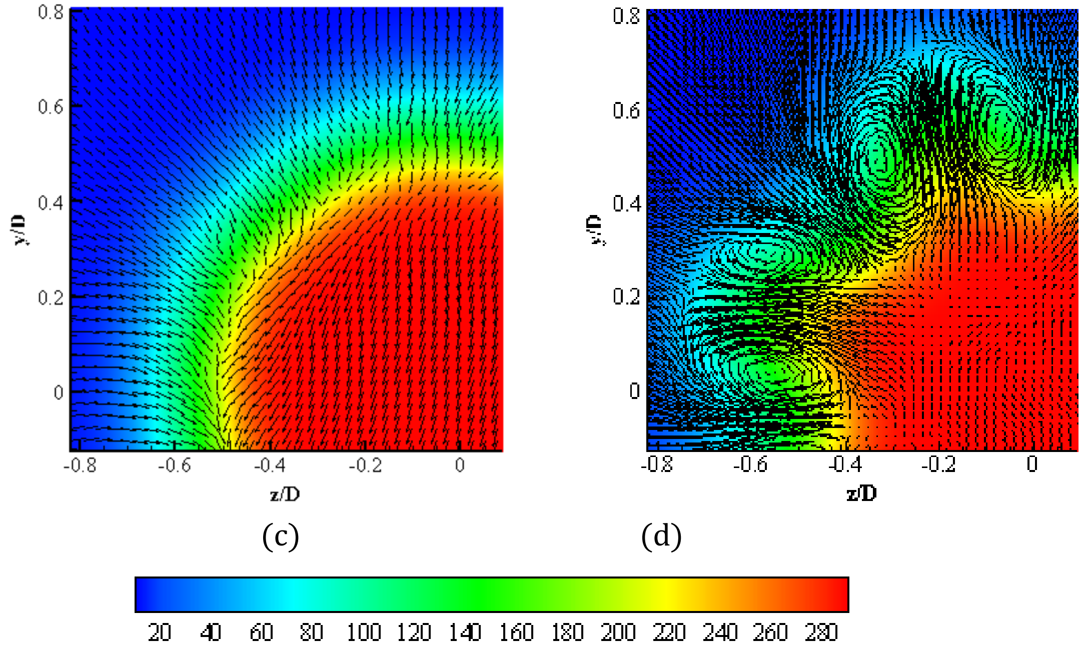


Fig. 6: Average streamwise velocity distribution [U_z, m/s] at x/D = 2.5 showing, (a) baseline (b) control cases. A zoomed in view of the top-left quadrant of the average streamwise velocity field showing the in-plane vectors for (c) baseline (d) control cases. The control case clearly shows the presence of strong streamwise vortex pairs induced as a result of high-frequency forcing.

Far field acoustic results showed a modest reduction in noise levels for low to moderate frequencies for all observation angles. A maximum SPL reduction of approximately 2dB was observed for St_D = 0.6 and St_D = 0.3 for microphones at 90° and 150°, respectively. Similar to near field acoustic results, increase in high frequency noise, mostly dominated by the actuator's resonant noise, was observed at all polar angles for St_D > 1.6 (f ≈18 kHz). In addition to this, small increases in noise levels, perhaps resulting from forcing of fine scale turbulence at high-frequencies, were observed for St_D > 2.6. OASPL reduction of approximately 1 dB was obtained for microphones at 90° and 150°. The OASPL here was calculated between St_D = 0 and St_D = 1.6, where St_D = 1.6 is the cross-over Strouhal number after which the increase in high-frequency noise occurs.

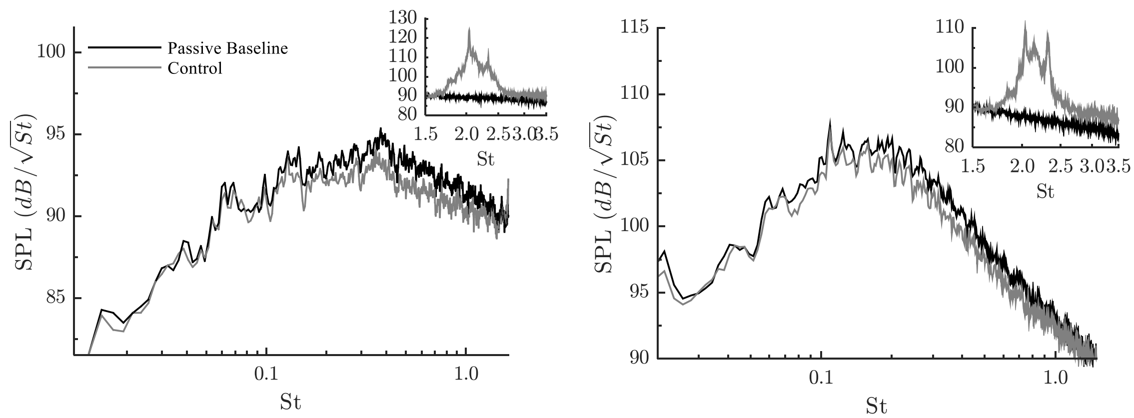


Fig. 7: Acoustic spectra for Mach 0.9 jet (NPR = 1.69) with and without high-frequency actuation showing (a) 90° (b) 150°. Inset: Increase in high frequency noise due to the actuator. The crossover Strouhal number (St_D = 1.6) coincides with the onset of actuator peak.

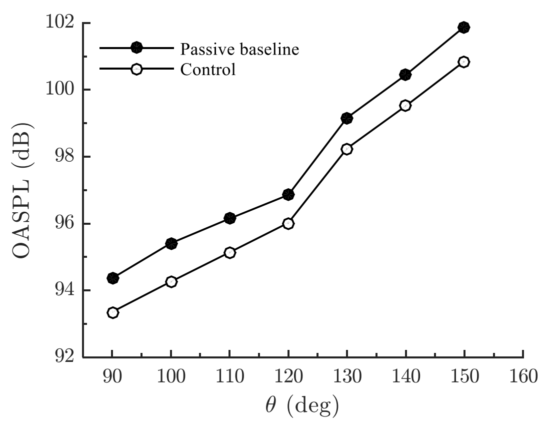


Fig. 8: Directivity showing reductions in OASPL levels across all polar angles. OASPL is calculated between St_D = 0 and St_D = 1.6.

Acoustic spectra as well as the far-field OASPL distribution clearly show that acoustic benefit in the far-field can be obtained by influencing the initial mixing layer of the jet. It is well known that the thin shear layer of an axisymmetric jet supports a range of instability modes. Many investigations have demonstrated that large scale coherent structures, that are known to be the most dominant source of aft angle noise, are manifestations of the growth of instabilities in the initial shear layer. The large scale structures, whose length scale are proportional to the jet exit diameter, are known to be primarily responsible for low frequency noise (St_D < 1). Therefore, observed reduction at low to moderate frequencies (St_D < 1.6) for all polar angles is suggestive of the lowered amplitudes of the acoustically dominant large scale structures. However, details on the mechanisms associated with this control method is not well understood and is part of ongoing research at Florida State University. Flow field measurements along with far-field acoustic data suggest that there may be two mechanisms involved with high-frequency forcing. The first involves reduction of mean shear by thickening of the initial shear layer. The growth of instability waves and hence turbulence production is driven by high mean shear in the initial region of the jet. The emergence of strong streamwise vorticity increases the local shear layer thickness, potentially making the jet less receptive to unstable modes. Additionally, it may lead to lowered growth rates of the existing instability waves. These results are comparable to noise reduction and turbulence suppression obtained with steady fluidic microjets. In addition to this, there may be a second mechanism associated with the unsteady component of the microjets forced into the shear layer at high frequencies. Small scale turbulence at high frequencies may draw energy from the mean shear resulting in lowered growth rate of low frequency noise sources. Moreover, these shorter wave length structures are at scales that are closer to the dissipative scale, and therefore may saturate and dissipate closer to the jet exit. These possible mechanisms of control are currently being investigated. *Results from this investigation was presented at the **54th AIAA Aerospace Sciences Meeting, AIAA Science and Technology Forum and Exposition 2016, San Diego, CA (AIAA 2016-0527).***

<u>Free Jet Noise Cotnrol Using Upstream Perturbation Seeding</u>

This is a novel flow-noise control strategy which is significantly different from previous methods employed for high-speed free jets. What distinguishes this approach from previous work is that here we attempt to "pre-condition" the internal nozzle flow boundary layer and thus rearrange the free shear layer initial conditions in a manner to make the free jet flow more amenable to effective control. In its ultimate implementation, the control strategy is based on two separate sets of actuators that are placed at key points in the flow field of interest. Herein, the first actuator set is strategically located upstream of the most receptive region of the flow. The location for the first actuator set corresponds to the jet nozzle internal boundary layer region. A second actuator set is placed downstream of the first actuator set and preferably in the vicinity of the most receptive region of the flow. This location corresponds to the vicinity of the nozzle exit plane. The task of the first actuator set is to introduce disturbances specifically tailored to help generate coherent organized structures within the boundary layer. This strategic perturbation of the internal nozzle boundary layer is designed to "add coherence" to a complex flow field that is normally comprised of broadband fluctuations spread over a wide range of length and time scales.

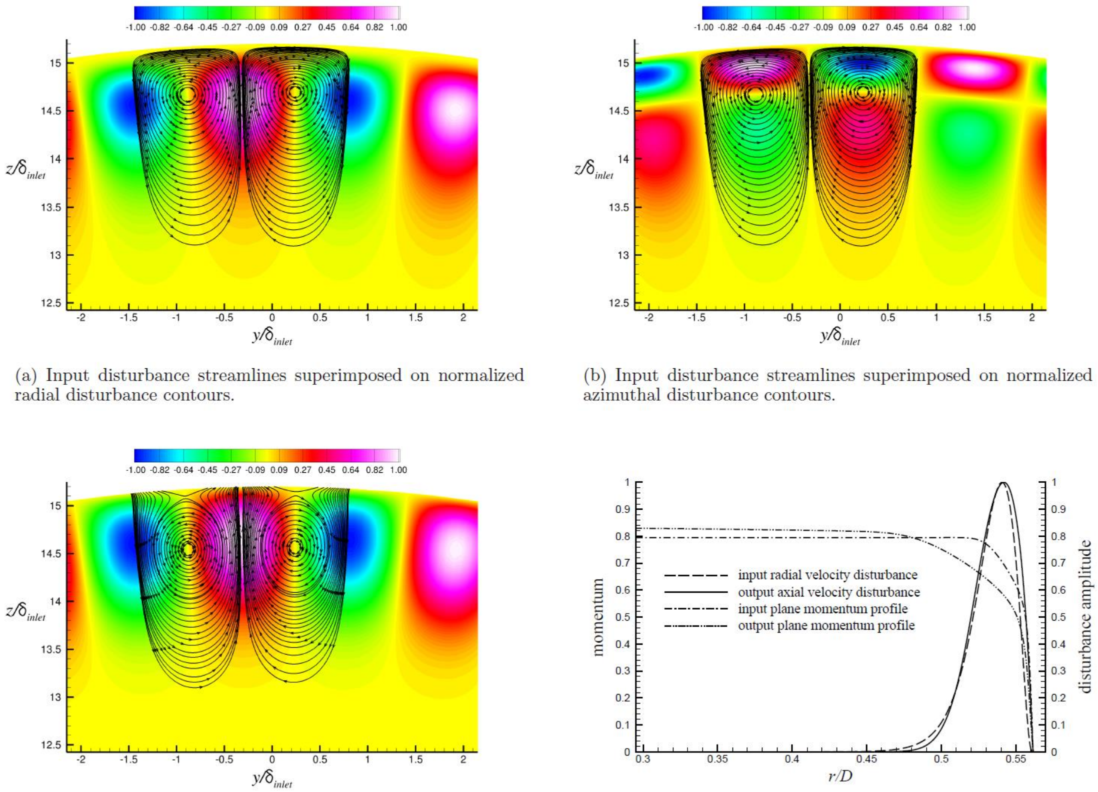
We accomplish this by developing and implementing *optimal perturbation theory* which predict the most unstable modes that are expected to grow preferentially inside the nozzle. A computational analysis tool based on the optimal perturbation theory has been utilized to calculate the optimally-growing disturbances in an initially turbulent boundary layer. The test geometry considered in this study contains a convergent nozzle, which generates a Mach 0.9 round jet, preceded by a straight circular pipe section. The relevant stability equations are derived using both the standard decomposition and the triple decomposition. In the standard decomposition, a given flow quantity is represented as the sum of its mean value and the organized disturbance. The triple decomposition also contains the same two components but additionally includes the turbulence motion.

Representative Optimal Perturbation Theory and Results for Pipe-Nozzle Flow

We summarize the main observations from the calculations based on the standard decomposition first. These results indicate that the optimally-growing disturbances in the initially turbulent boundary layer appear in the form of longitudinal counter-rotating vortex pairs (CVPs). Such disturbances are introduced at various axial stations within the circular pipe section to facilitate disturbance energy amplification upstream of the favorable pressure gradient zone within the convergent nozzle, which has a stabilizing effect on disturbance growth. The introduced disturbances grow with axial distance inside the straight pipe section and reach a global peak in the vicinity of the convergent nozzle inlet. Effects of temporal frequency, disturbance input and output plane locations, as well as separation distance between output and input planes are investigated. For a fixed output plane, the azimuthal wavenumber of the disturbances, which is equivalent to the number of CVPs, generally decreases with increasing separation distance while the disturbance energy amplification ratio increases with separation distance. Increasing the separation distance implies that the input disturbances would have a greater axial length over which to grow and develop. In such a scenario, a lower azimuthal wavenumber would allow the longitudinal vortices to grow over the given axial separation distance while avoiding destructive interference for the sake of maximal energy amplification. The results also indicate that for all separation distances, the disturbance amplification ratios decay monotonically with increasing temporal frequency and the strongest amplification occurs for zero temporal frequency, which corresponds to steady input disturbances. A representative result is shown in Fig. 9 which depict the flow properties in the input and output planes. Also clearly seen in Figs. 9a -9c are the CVPs induced due to actuation.

The general trends observed from the calculations based on the triple decomposition analysis are qualitatively similar to those from the standard decomposition. However, there is a significant change in the quantitative nature of the predictions. It is found that the interaction between the organized disturbance and turbulence manifests itself in the form of considerably reduced disturbance energy amplification ratios and shifts the optimal azimuthal wavenumber to values which are relatively lower than those predicted by the standard decomposition analysis. From a physical point of view, this detrimental effect on the optimal disturbance growth arises as the organized disturbance encounters additional “resistance” in the form of eddy viscosity due to the boundary layer turbulence, which brings in diffusive effects into play. Consequently, one may hypothesize that a larger-sized organized structure (which corresponds to low azimuthal wavenumber) would be able to survive such detrimental turbulence interaction effects better than a relatively smaller-sized organized structure could. We believe this hypothesis provides a feasible explanation as to why the triple decomposition analysis yields peak azimuthal wavenumbers that are relatively lower than those predicted by the standard decomposition analysis.

As the two decomposition methods yield substantially different quantitative results, complementary experiments are helpful in determining which of the trends predicted by the two decomposition methods is more credible. A preliminary set of experiments and analysis and simulation were conducted late last year and yearly this year, examining the validity of this approach in a more canonical flow, a flat plate turbulent boundary. This complementary research is in large part supported through an NSF grant - additional experiments are planned in the near future. The findings from this theoretical study are reported in a journal paper (Uzun et al.[26]) that is currently in preparation. The approach and initial results of this study is briefly discussed in the following section. In addition, related work on stability analysis of high speed jets in context of noise reduction was also published in the AIAA Journal earlier this year[27]



(a) Input disturbance streamlines superimposed on normalized radial disturbance contours.

(b) Input disturbance streamlines superimposed on normalized azimuthal disturbance contours.

Fig 9 - Optimally-growing input and corresponding output disturbances for m = 41, $St = 0$, $x_{in}/D = -3$ and $x_{out}/D = -0.7$. (from Ali et al., in preparation and included in Appendix)

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Role of Optimal Disturbances in a Flat Plate Turbulent Boundary Layer

The first representative test case geometry chosen for the theoretical analysis using optimal disturbances consisted of a circular pipe, where disturbances are introduced. The pipe is followed by a convergent nozzle which generates a Mach 0.9 round jet - the results of the pipe-nozzle study were presented above. In order the further examine the validity, and limits, of the role of optimal disturbances in turbulent flows, the developed theoretical and computational tools have also been applied to the *incompressible turbulent boundary developing over a flat plate*. This canonical flow field allows for an in depth analysis of the spatial development of optimally amplified disturbances, the preferential selection of the spatio-temporal scales by the turbulent mean flow, their potential interaction with background turbulence, and the effects of flow

Reynolds number. The incompressible turbulent boundary layer has been the topic of intense research across experimental, computational and theoretical fronts, including previous stability-based analyses. As such, there exists a large database of literature for a direct comparison of the optimal disturbance results with both the natural, energetic motions in turbulent boundary layers and previous control schemes that is not available for the nozzle geometry. In this regard, this secondary study augments the more complex pipe-nozzle configuration.

Similar to the pipe-nozzle configuration, the optimal disturbances are found to consist of input streamwise vortices that induce streamwise velocity streaks. In contrast to previous stability analyses involving turbulent boundary layers, which have considered a locally parallel flow, the results indicate that the spatial development of the mean flow plays a critical role in the selection of the streamwise, spanwise and wall-normal scales of the most amplified disturbances. In general, the optimal spanwise spacing is found to be a strong function of the streamwise separation between the input forcing disturbance and the optimal flow response, with smaller scales being associated with shorter streamwise separation. This has the somewhat intuitive implication that a 'global' optimal perturbation many not be applied for all potential control schemes, but must be selected based on geometric considerations for optimal control. The effect of the background turbulence on the development of the optimal perturbations were also studied in detail. Associated with the triple decomposition, an eddy viscosity determined from the mean flow is included to model these interactions. Similar to previous temporal stability analyses, two peaks in the energy amplification are found: one that scales with inner, viscous units and a second, dominant peak that scales in outer units based on the boundary layer height. While the dominant peak corresponds to structures roughly half the size of those reported in previous temporal analyses, it still greatly over-predicts the well accepted scales in natural turbulent boundary layers. The main conclusion is that the use of the eddy viscosity, based on the turbulent mean flow, either tends to overemphasize the effect of background turbulence on the selection of optimal scales, or is inappropriate. This conclusion is substantiated by the optimal disturbance results computed in the absence of the eddy viscosity. In this case, we find structures that are in excellent agreement with the natural scales observed in real turbulent boundary layers.

Previous studies on optimally amplified perturbations have generally identified stationary (zero-frequency) disturbances as the most globally amplified. While these stationary disturbances have a clear connection with fixed passive or active control actuators, their relation to natural, convective motions in real turbulent flows is ambiguous. The current results indicate that traveling wave solutions, those having finite streamwise wavelengths and temporal frequencies, are capable of achieving larger energy amplification for unit forcing than their stationary counterparts. The most amplified modes are found to propagate downstream with a convective velocity equal to the local turbulent mean flow. In particular, these traveling wave disturbances show excellent agreement with the large-scale energetic motions observed in turbulent boundary layers. This theoretical and computational study, which builds upon the outcomes of this grant, is continuing under an NSF grant.

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27. Uzun, A., Davis, T. B., Alvi, F. S., Colonius, T. and Hussaini, M. Y., "Spatial Stability Analysis of Subsonic Jets Modified for Low-Frequency Noise Reduction," *AIAA Journal*, **53**, pp. 2335-2358, 2015.

Appendices & List of Publications

To date, the results of research partially supported through this project has resulted in **6 Conference papers** and **3 Journal articles.** In addition 1 journal article is under review and at least 2 more are under preparation. They are listed below and included as separate documents.

Conference Publications

Craft, J., Upadhyay, P., Worden, T., and Alvi, F. S., "Characterization and Validation of an Anechoic Facility for High-Temperature Jet Noise Studies", *AIAA Paper,* 2016-3800, 2016.

Upadhyay, P., Valentich, G and Alvi, F. "Flow and Acoustic Features of a Mach 0.9 Jet Using High Frequency Excitation," *AIAA Paper*, 2016-0527, 2016.

Worden, T. J., Shih, C. and Alvi, F. S., "Supersonic Jet Impingement on a Model-scale Jet Blast Deflector," *AIAA Paper,* 2016-1015, 2016.

Upadhyay, P., Davis, T. and Alvi, F., "Active Control of Mach 0.9 Jet Using High Frequency Excitation," *AIAA Paper,* 2015-0299, 2015.

Kreth, P., Upadhyay, P., Alvi, F. and Shih, C., "Recent Developments in High Bandwidth Pulsed Micro-Actuators for Fluid Applications," Proceedings, the 9th International Conference on Nano/Molecular Medicine and Engineering, Hawaii, Nov. 15-18, 2015.

Upadhyay, P., Gustavsson, J., and Alvi, F. S., "Ultra-High-Frequency Actuators for Jet Noise Control," *AIAA Paper*, 2013-2476, 2013.

Journal Publications

Kreth. P., Ali, M. Y., Fernandez, E. and Alvi, F. S, "Velocity Field Measurements on High-frequency, Supersonic Microactuators," *Experiments in Fluids*, **57.5**, pp. 1-13, 2016. doi: 10.1007/s00348-016-2169-x

Upadhyay, P., Gustavsson, J. P. and Alvi, F. S, "Development and Characterization of High Frequency Resonance Enhanced Microjet Actuators for Control of High Speed Jets," *Experiments in Fluids*, **57.5**, pp. 1-16, 2016. doi: 10.1007/s00348-016-2164-2

Uzun, A., Alvi, F. S., Colonius, T., and Hussaini, M. Y., "Spatial Stability Analysis of Subsonic Jets Modified for Low- Frequency Noise Reduction," *AIAA Journal*, **53**(8), pp.2335-2358, 2015. doi: 10.2514/1.J053719

Under Review or Preparation

Uzun, A., Alvi, F. S., and Hussaini, M. Y., “Optimally-growing boundary layer disturbances in a convergent nozzle preceded by a circular pipe,” submitted to the *Theoretical and Computational Fluid Dynamics*, Spring 2016.

Upadhyay, P., Valentich G.M., Alvi, F.S., “Flow and acoustic features of a Mach 0.9 free jet using high-frequency excitation.” *Experiments in Fluids* (in preparation)